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Dwelling, rescanning, and skipping of distractors explain search efficiency in difficult search better than guidance by the target

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ABSTRACT

Prominent models of overt and covert visual search focus on explaining search efficiency by visual guidance. That some searches are fast whereas others are slow is explained by the ability of the target to guide attention to the target's position. Comparably little attention is given to other variables that might also influence search efficiency, such as dwelling on distractors, skipping distractors, and revisiting distractors. Here, we examine the relative contributions of dwelling, skipping, rescanning, and the use of visual guidance, in explaining visual search times in general, and the similarity effect in particular. The hallmark of the similarity effect is more efficient search for a target that is dissimilar to the distractors compared to a target that is similar to the distractors. In the present experiment, participants have to find an emotional face target among nine neutral face non-targets. In different blocks, the target is either more or less similar to the non-targets. Eye-tracking is used to separately measure selection latency, dwelling on distractors, and skipping and revisiting of distractors. As expected, visual search times show a large similarity effect. Similarity also has strong effects on dwelling, skipping, and revisiting, but only weak effects on visual guidance. Regression analyses show that dwelling, skipping, and revisiting determine search times on trial level. The influence of dwelling and revisiting is stronger in target absent than in target present trials, whereas the opposite is true for skipping. The similarity effect is best explained by dwelling. Additionally, including a measure of guidance does not yield substantial benefits. In sum, results indicate that guidance by the target is not the sole principle behind fast search; rather, distractors are less often skipped, more often visited, and longer dwelled on in slow search conditions.

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Laboratory and everyday tasks often entail visual search, where covert attention or gaze is shifted with the aim to focus on and selectively perceive and process currently needed visual information. Visual search is also an important topic of research (Duncan & Humphreys, 1989; Hulleman & Olivers, 2017; Koch & Ullman, 1985; Neisser, 1964; Wolfe, Cave, & Franzel, 1989; Zelinsky, 2008). In a typical experimental visual search task, a single target is presented among a varying number of distractors and the time taken to find the target is measured.

A fundamental challenge of visual search theory is to explain why some searches are easy and fast, whereas others are difficult and slow. Search difficulty is measured by the slope of the linear function relating search time to set size, which is the number of items in a display. This measure of search efficiency varies from around 0 ms/item in very efficient search to over

100 ms/item in very inefficient search. The hallmark of efficient search is that adding distractors to a search display does not slow down the time to find the target, which is indexed by a flat slope of the function relating search time to set size. In contrast, inefficient search means that search time depends heavily on the number of presented items, which is indexed by a steep slope of the function.

Different principles have been proposed to explain why some searches are easy whereas others are hard. The most prominent one is *guidance* by the target which is implemented in models such as Guided Search (GS; Wolfe et al., 1989; Wolfe, 2007) or the Target Acquisition Model (TAM; Zelinsky, 2008). For example, in GS, the assumed characteristics of the target, which are represented in the target template, interact with information extracted from the search display. For each location, evidence for a target is

accumulated in an activation map, where the amount of activation at one location corresponds to the evidence that the location contains the target. A gradient descent algorithm is used to schedule the sequential shifts of attention. A high peak in the activation map at the target's location thus leads to an early focusing of attention on that location, and search is efficient. When some of the non-targets share features with the target, multiple peaks arise in the activation map and, because of inherent noise in the system, the target location may not always have the highest activation in the activation map. To summarize, according to the concept of guidance, search efficiency is a function of activation in the activation map at the target location relative to the non-target locations. Search is easy when the target provides a strong guidance signal, and it is difficult when the guidance signal by the target is not much stronger than that of the non-targets.

A complementary approach focusses on the processing of the distractors, which will be termed *distractor rejection* here. Selecting, processing, and rejecting distractors is the activity that renders search inefficient. Several principles regarding distractor rejection have been suggested. For instance, Duncan and Humphreys (1989) propose that distractors that are relatively similar to each other and relatively different from the target can be rejected at once as a group. Thus, *distractor grouping* provides the possible basis for efficient search, and search efficiency is related to the size of the groups of simultaneously rejected distractors (the bigger, the better). Hulleman and Olivers (2017) assume that search efficiency is related to the size of the *functional view field* (FVF). The FVF can be regarded as a spatially defined region in which stimuli are processed in parallel. According to this theory, FVF size is adjusted according to the level of task difficulty. Easy searches allow the FVF to be large, whereas hard searches require small a FVF. With a large FVF, several stimuli are processed within a single fixation; with a small FVF, every stimulus may require a separate fixation. Critically, when the FVF is small, *rescanning* of distractors can further reduce search efficiency. As only a limited number of stimulus positions is stored in working memory, some locations are analysed more than once. Thus, when the search display comprises multiple non-targets and the FVF is small, the positions of already selected and rejected distractors may be lost and would be selected again, which further impairs

search efficiency (see Humphreys & Müller, 1993). In addition to distractor grouping and rescanning, some findings indicate that *dwelling* on distractors contribute to search efficiency. While current models of visual search, such as GS, TAM, or FVF theory, assume that distractor dwell time is constant, several studies found variations in dwell time. For instance, Hooze and Erkelens (1998) found sizable differences in fixation duration depending on visual search difficulty. Becker (2011) showed that dwell time in visual search depends on both target-distractor similarity and perceptual difficulty, and Gould (1973) found fixation duration to be dependent on memory set size, that is, the number of possible targets that are simultaneously searched for. Finally, Horstmann, Herwig, and Becker (2016) found overall scanning speed to be strongly influenced by distractor dwelling in a difficult search task.

The problem of absent trials

In many visual search experiments, the target is presented in half of the trials (target trials), but is absent in the other half of the trials (absent trials). A somewhat underestimated observation is that efficiency in present trials is strongly correlated with efficiency in absent trials. As a general rule, the search slope in absent trials is about twice as high as the search slope in target trials, for any given level of search efficiency (Wolfe, 1998). If the slope is 20 ms/item in present trials, it is about 40 ms/item in absent trials; if the slope is 50 ms/item in target trials, it is about 100 ms/item in absent trials. The principle target/absent slope ratio is easily explained by assuming serial self-terminating search that continues until the target is found in present trials and until no distractor is left in absent trials.

That this ratio is roughly preserved with different degrees of search efficiency is easily explained by models focusing on distractor rejection (e.g., Horstmann, Lipp, & Becker, 2012), but poses a problem for models that focus on target guidance.

A distractor rejection account of the preserved present/absent ratio could make the following claims. Until the target is found, search proceeds the same in present trials as in the absent trials, and consists of the same sequence of selecting, processing, and rejecting distractors. Distractor processing is stopped when all distractors have been rejected or

when the target is found, which is on average after half of the display has been examined. Distractor processing is thus the commonality between present and absent trials, and this commonality readily explains why present and absent trial search times are highly correlated. Whatever the size of the group of jointly rejected distractors, the size of FVF, or the dwell time for a distractor might be in a given search, it is the same in present and in absent trials – hence the preserved ratio.

For a model that uses guidance as the sole principle accounting for efficiency it is difficult to explain why target absent trials should vary at all. A target absent judgment is issued when the last distractor has been examined and found not to be the target. Chun and Wolfe (1996; see also Zelinsky, Adeli, Peng & Samaras, 2013) solved this problem by providing an additional principle – an adaptive threshold for search continuation. This adaptive threshold concept essentially holds that search is continued for candidate objects above an activation threshold, with the activation of the candidate objects reflecting the similarity to the target. In a difficult task, the target is similar to the distractors. Thus, all distractors have to be examined before it can be safely concluded that there is no target in the display. In an easy search, the target is dissimilar to the distractors and is correspondingly the sole candidate with a high activation, whereas distractor candidates generally have a low activation. Usually it should suffice to check only the highly activated candidate(s) in an absent trial, and stop searching after that. This could be done by adjusting a threshold between the expected activation values of target and distractor, respectively. The adjustable threshold effectively regulates how many items in an absent trial are skipped (i.e., not inspected at all) before the decision is made that there is no target in the display. Thus, a fourth possible way of explaining differences in search efficiency is by distractor skipping, which is derived from target guidance (or expected/estimated target guidance).

Horstmann et al. (2016) explicitly tested some of the principles in an eye tracking experiment. They focussed on dwelling, rescanning, and skipping of items during search. The visual search task was generally quite difficult, as it presented natural images of faces with the task to detect the single angry face among neutral faces, if present. Search efficiency was manipulated through target distractor similarity.

In the easy search blocks, the target was rather dissimilar to the distractors, as it was the only face displaying a frown and an open mouth. In hard search blocks, the target was similar to the distractors and differed only in displaying a frown. Results revealed the well-known *similarity effect* (e.g., Duncan & Humphreys, 1989), with longer search times for similar than for dissimilar targets. More importantly, similarity dramatically elongated dwell times, in present and in absent trials. In contrast, skipping was not much influenced by similarity. As noted previously, skipping should be directly influenced by adjusting the threshold and is the proximal cause of search efficiency differences in absent trials as assumed by guidance models of visual search. Using dwelling, skipping, and rescanning as predictors of search times in a linear regression revealed significant effects of dwelling and skipping, but not of rescanning in absent trials. This study thus supported the distractor rejection principle of search efficiency.

However, a sceptic might question the generality of Horstmann et al.'s (2016) results. In particular, it might be contended that the presented set size is rather low (five items, of which only four were target candidates), and that the display layout was highly structured (the faces were presented at the four vertices of an imagined square) and predictable (i.e., the same in every trial). Low set sizes in turn might discourage participants from skipping target candidates in absent trials because searching through all stimuli in the display is relatively easy and does not incur high costs. Moreover, a highly structured and predictable display might discourage participants from using guidance, because a systematic scan is easily pre-programmed. Finally, low set sizes may lead to untypically low rescanning rates, when the number of stimulus positions matches the memory limit for already visited positions.

The present study

A first goal of the present study was to probe into the generality of previous findings, by critically testing what kind of distractor rejection processes most strongly determine search times when the search displays are less predictable and contain more stimuli. A second major aim of the study was to test possible contributions of target guidance to search efficiency.

To assess distinct distractor rejection processes, we will centrally assess variations in distractor dwell time, as well as skipping and revisiting of distractors in

search displays with 10 faces, an irregular display layout, and randomly varying stimulus positions. The general strategy will be to first analyse the effect of similarity on overall search time, dwelling, skipping, revisiting, and guidance by using standard analyses (ANOVAs). In a second step, we will use correlational analyses to assess how well variations in dwelling, skipping, and revisiting explain variations in overall dwell times.

To test possible contributions of target guidance, we extended the regression analysis to target trials. Horstmann et al. had focused on target absent trials, because absent trials would reflect pure distractor processing. It remains an open question whether dwelling on distractors is also an important factor in target present trial performance, or whether other factors (e.g., target guidance) play a more important role. Thus, the present study sought to clarify how much distractor rejection and, in particular, dwelling on the distractors contributes to search when the target is actually present and can guide attention directly.

A third goal of the present study was to test whether correlations between dwelling and search performance could also be observed on the level of individual trials. Correlations between dwelling and search efficiency have been found on the level of condition averages (Horstmann et al., 2016). Because correlations on the level of condition averages might not necessarily reflect the mechanisms driving dynamic search processes on a given trial, we were interested in examining the impact of our variables of dwelling, skipping, and revisiting on the search time within that trial.

Methods

Participants

Twelve students participated in the study, eight women and four men, with a mean age of 23.25 ($SD = 2.73$) years. They received €3 for their 30 min participation.

Stimuli

Stimuli were drawn from the NimStim stimulus set (Tottenham et al., 2009). Five female models and five male models provided a neutral face and two variants of friendly faces each, one with an open mouth and visible teeth (dissimilar target) and one with a closed

mouth (similar target, see Figure 1). Neutral faces all had a closed mouth. Thus, a total of 30 pictures of faces were used. Each colour picture subtended 77×99 pixels ($2.1^\circ \times 2.8^\circ$), and was coded as a bit map with a colour depth of 24 bits (see Figure 1 for an example of the three expressions that were used from each model).

Search displays consisted of 10 pictures presented in 10 randomly selected cells, excluding the centre position, of a 3×5 matrix with a horizontal spacing of 100 pixels (2.8°) and a vertical spacing of 130 pixels (3.6°). The centre position, where also the fixation stimulus appeared, was never used for a stimulus. Pictures were presented centred on the cells of the matrix, with an additional random jitter of 5 ± 5 pixels horizontally and vertically.

Apparatus

Stimuli were presented on a 19-inch display CRT-monitor (100-Hz refresh rate, resolution 1024×768 pixels) at a distance of 71 cm. A video-based tower-mounted eye tracker (EyeLink 1000, SR Research, Ontario, Canada) with a sampling rate of 1000 Hz was used for the recording of eye movements. The participants' head was stabilized by a chin and forehead rest and, in all participants, the right eye was monitored. Before the experiment commenced, the eye tracker was calibrated using a 9-point calibration. The experiment was programmed using Experiment Builder 1.10.165 (SR Research, Ontario, Canada), and preprocessed using Data Viewer 2.2.1 (SR Research, Ontario, Canada).

Design

The experiment comprised five blocks, which differed only in the target category (open versus closed mouth targets, or distractor-dissimilar versus distractor-similar target, respectively). Each block contained 20 trials, 10 of which were target present trials and 10 were target absent trials. Blocks with similar targets alternated with blocks with dissimilar targets. Half of the participants started with a similar target block. The first block was considered as practice and omitted from the analysis.

For each trial, one of the 10 models (facial identities) was randomly selected. If the trial was designated as a target present trial, this model displayed the



Figure 1. Examples of the neutral face (left), the similar target (centre), and the dissimilar target (right).

target emotion; if the trial was designated as a target absent trial, this model showed a neutral expression. Each model was used twice in a block, once as a target and once with a neutral facial expression. The remaining nine stimulus positions were filled randomly with the remaining nine models which all displayed a neutral expression. Thus, on target absent trials, search displays consisted of pictures of 10 different people showing a neutral face. For each target present trial, there was a corresponding target absent trial where the same model showed a neutral expression. Thus, these “foil targets” corresponded in identity to the actual targets. The composition of the displays was determined anew for each trial and participant.

Procedure

Each trial started with a fixation control, which was terminated with a key press (with the left hand) that also initiated the presentation of the search display. The task was to indicate with a key press (index or middle finger of the right hand) whether one of the 10 possible targets (all friendly faces) was presented in a trial. The search display was presented until the response key press was registered. Prior to each block (dissimilar vs. similar targets), the 10 possible targets were displayed side by side on the monitor for ad lib inspection, with the aim of providing an overview of their appearance.

Eye tracking data preprocessing

Raw eye position data were parsed by eye tracker's standard experimental setting which uses a speed threshold (30°/s) and an acceleration threshold

(8000°/s²) to detect saccades. Areas of interest (AOIs) were defined that enclosed the face pictures almost exactly (i.e., they were 1–2 pixels larger than the picture).

Results

Error rates

Overall proportion correct was $M = .96$. An ANOVA computed over the proportion of correct responses with the variables similarity (similar vs. dissimilar) and target presence (present vs. absent) revealed a significant main effect for presence only, $F(1,11) = 14.01$, $p = .003$, $\eta_G^2 = .23$ (other F s < 1.94 all p s $> .19$, $\eta_G^2 < .03$). Accuracy was higher for present than absent trials (.99 vs. .94).

Reaction times

Trials with errors in the search task or in which RTs were implausibly short (< 300 ms) or exceeded the .99th percentile (5849 ms) of the RT distribution were discarded from this and all following analyses (Figure 2). An ANOVA computed over the mean RTs with the variables similarity (similar vs. dissimilar) and target presence (present vs. absent) revealed that both main effects were significant (presence: $F(1,11) = 116.71$, $\eta_G^2 = .59$; similarity: $F(1,11) = 119.61$, $\eta_G^2 = .53$; all p s $< .001$). Target present RTs were shorter than target absent RTs (1780 ms vs. 2844 ms), and dissimilar targets rendered lower RTs than similar targets (1844 ms vs. 2780 ms). The similarity effect was stronger in target absent trials (see Figure 2), as revealed by the significant Presence \times Similarity interaction, $F(1,11) = 32.65$, $p < .001$, $\eta_G^2 = .10$. Thus, we were able to establish a strong

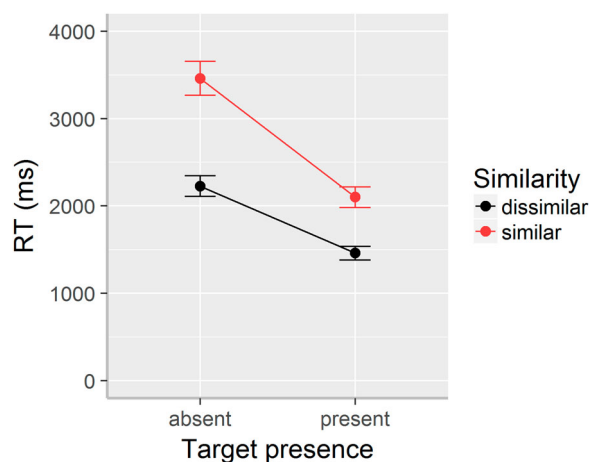


Figure 2. Mean RTs for trials with high and low target-distractor similarity, in target absent and present trials, respectively. Error bars are standard errors (i.e., SD / \sqrt{N}) of the means.

similarity effect, which is more pronounced in target absent than in target present trials, as expected.

Dwell times on targets/foil targets and distractors

Fixations that were either very short (40 ms, four instances) or exceeding the 99th percentile of the dwell time distribution (1471 ms, 62 instances) were excluded from the analyses of dwell times. Figure 3 (a) provides an overview of the first run dwell times on distractors and targets in target present trials, and on distractors and foil targets in target absent trials. First run dwell times are the sum of fixation durations during the first continuous visit on a stimulus; thus, this measure maintains a clear separation between dwelling and revisiting of stimuli. Dwell times were computed only for stimuli that were actually visited; thus, this measure is also not influenced by the number of visited stimuli.

An ANOVA of the dwell times with the variables target presence (present vs. absent), similarity (similar vs. dissimilar), and stimulus type (distractor

vs. target/foil target) rendered significant main effects for all variables. The dwell time on a stimulus was longer in target present than in target absent trials, $F(1,11) = 83.57$, $p < .001$, $\eta_G^2 = .53$, longer in the difficult search condition (similar targets), $F(1,11) = 14.86$, $p = .003$, $\eta_G^2 = .04$, and longer for the target/foil stimuli than on the distractors, $F(1,11) = 87.76$, $p < .001$, $\eta_G^2 = .56$. Among the interaction effects, only the Presence \times Stimulus type interaction was significant, $F(1,11) = 74.44$, $p < .001$, $\eta_G^2 = .56$ (other $F_s < 1$, $p_s > .46$, $\eta_G^2_s < .01$). It was due to the much longer dwell times on targets (747 ms) than on distractors (217 ms) in target present trials, $t(11) = 9.03$, $p < .001$, $d_z = 1.83$, whereas there was no difference between distractors (236 ms) and foil targets (234 ms) in target absent trials, $t(11) = 0.25$, $p = .807$, $d_z = 0.02$. The similarity effect was due to longer dwell times on similar than on dissimilar stimuli, with an average difference of 47 ms.

Proportion of fixated and skipped stimuli

Figure 3(b) provides an overview of the proportion of skipped distractors and targets in target present trials, and on distractors¹ and foil targets in target absent trials. As one of our variables of interest is skipping, we will present the data accordingly as the proportion of skipped stimuli.

An ANOVA of the skipping proportions with the variables target presence (present vs. absent), similarity (similar vs. dissimilar), and stimulus type (distractor vs. target/foil target) rendered significant effects for all variables and interactions ($F_s > 12.54$, $p_s < .005$, $\eta_G^2_s > .03$). To clarify the complex interaction pattern, ANOVAs were conducted separately for target present and target absent trials.

For target absent trials, only the main effect for similarity was significant, $F(1,11) = 58.78$, $p < .001$, $\eta_G^2 = .45$, with a lower proportion of skipping on

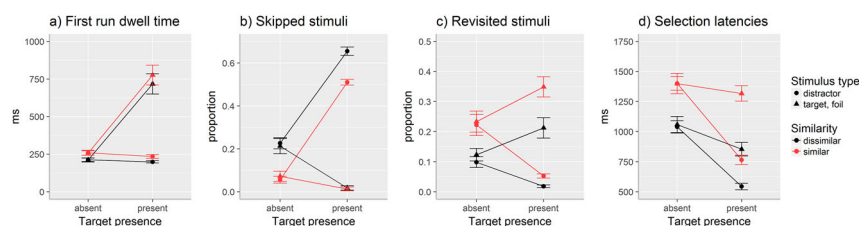


Figure 3. Mean dwell times, proportions of skipped stimuli, proportions of revisited stimuli, and fixation latencies for blocks with high and low target-distractor similarity in target and present trials. Error bars are standard errors (i.e., SD / \sqrt{N}) of the means.

similar stimuli (.06 vs. .22) (other F s < 1). The lack of an effect for stimulus type is expected because, from the viewpoint of the participant, the foil target is not different from the other distractors.

For target present trials, the main effects for similarity $F(1,11) = 99.93$, $p < .001$, $\eta_G^2 = .41$, and stimulus type, $F(1,11) = 1511.45$, $p < .001$, $\eta_G^2 = .98$, were significant, as was the interaction, $F(1,11) = 162.62$, $p < .001$, $\eta_G^2 = .38$. In target present trials, the target was almost always fixated both when it was similar (skipping probability = .01) and when it was dissimilar (skipping probability = .02) to the distractors, $t(11) = 1.05$, $p = .317$, $d_z = 0.17$. For the distractors, skipping probability depended on target-distractor similarity (as in the absent trials), $t(11) = 11.72$, $p < .001$, $d_z = 2.03$, with fewer distractors being skipped in trials with similar targets (.51) than with dissimilar targets (.65).

Revisiting

Figure 3(c) provides an overview of the proportions of revisits on distractors and targets in target present trials, and on distractors and foil targets in target absent trials. An ANOVA of the revisiting proportions with the variables presence (present vs. absent), similarity (similar vs. dissimilar), and stimulus type (distractor vs. target/foil target) rendered main effects of similarity, $F(1,11) = 30.21$, $p < .001$, $\eta_G^2 = .25$, and stimulus type, $F(1,11) = 50.06$, $p < .001$, $\eta_G^2 = .36$. Two significant interactions modified the main effects: Presence \times Stimulus type, $F(1,11) = 79.60$, $p < .001$, $\eta_G^2 = .30$, and Presence \times Stimulus type \times Similarity, $F(1,11) = 10.44$, $p = .008$, $\eta_G^2 = .03$ (other F s < 1.80, η_G^2 s < .02).

To clarify the complex interaction pattern, two separate ANOVAs were conducted for target absent and target present trials. For target absent trials, only the main effect for similarity was significant, $F(1,11) = 18.55$, $p = .001$, $\eta_G^2 = .28$, reflecting a higher proportion of revisits on similar than dissimilar distractors (.23 vs. .11) (other F s < 1.05, η_G^2 s < .01).

For target present trials, the main effects for similarity $F(1,11) = 16.48$, $p = .002$, $\eta_G^2 = .22$, and stimulus type, $F(1,11) = 83.86$, $p < .001$, $\eta_G^2 = .70$, were significant, as was the interaction, $F(1,11) = 6.51$, $p = .027$, $\eta_G^2 = .09$. While the similarity effect was significant for both targets, $t(11) = 3.36$, $p = .006$, $d_z = 0.83$, and distractors, $t(11) = 5.75$, $p < .001$, $d_z = 1.13$, it was smaller for distractors ($\Delta = .03$) than for targets ($\Delta = .14$). In

other words, revisiting of distractors in present trials was barely influenced by similarity, whereas similar targets were revisited clearly more often than dissimilar targets.²

Guidance by the target

RT analysis already indicated that the target is found faster in the dissimilar than in the similar condition. Guidance would register in shorter fixation latencies on the target in the dissimilar than the similar condition, with selection latency being defined as the time from the display onset to the first gaze contact with a stimulus. However, shorter fixation latencies may be due to guidance, but also to shorter dwelling on distractors or less frequent rescanning of the distractors. These other factors, however, would also be active in target absent trials. Thus, to balance similarity effects on distractor processing, we compared selection latency for the target with the selection latency of the foil target within the same category of trials (i.e., for each target presence \times similarity combination). Latencies lower than 100 ms (61) or exceeding the 99th percentile of 3421 ms (62) were excluded from this and following analyses of selection latencies.

Figure 3(d) gives an overview of the mean selection latencies. The data for the distractors are dominated by the effect that, in absent trials, nearly all stimuli are gazed at and that therefore the average selection latency is relatively high. In contrast, a smaller number of distractors is visited in present trials: assuming no guidance, half of the distractors should be visited; assuming guidance, the number of distractors visited should be even less. Thus, the average selection latency for distractors should be considerably lower in present than in absent trials, and this is also reflected in the data.

An ANOVA of the target selection latencies with the variables presence (present vs. absent), similarity (similar vs. dissimilar), and stimulus type (distractor vs. target/foil target) revealed that, with the exception of the Presence \times Similarity interaction ($F < 1$, $\eta_G^2 < .01$), all main effects and interactions were significant, F s > 7.83, p s < .018, η_G^2 s > .02.

The further analysis focusses on the question whether the target is found faster than the foil target, and whether this effect is stronger for the dissimilar target; distractors were therefore not included. A 2×2 ANOVA with the variables target type (target

vs. foil) and similarity (similar vs. dissimilar) rendered main effects of target type, $F(1,11)=6.22$, $p=.030$, $\eta_G^2=.08$, and similarity, $F(1,11)=43.57$, $p<.001$, $\eta_G^2=.42$ (interaction, $F(1,11)=1.48$, $p=.249$, $\eta_G^2=.01$). Targets were fixated earlier than foil targets (1102 ms vs. 1259 ms), which indicates guidance. Surprisingly, dissimilar targets did not provide substantially more guidance than similar targets, which is indicated by the non-significant interaction effect. Targets and foil targets were fixated earlier when the task was to find the dissimilar than the similar target (950 ms vs. 1411 ms). Note that as this pertains to both targets and foil targets, it is not indicative of guidance but more probably due to distractor rejection processes.³

Contributions of dwelling, skipping, and rescanning to search times

Search times are basically the product of the number of fixations and their durations. However, to what degree do skipping, rescanning, and dwelling contribute to overall search time? We used a regression approach to examine this question. Table 1 presents the bivariate correlations between RT, revisiting rate, skipping rate, and dwell time on the level of trials separately for target absent and target present trials.

Figure 4 presents the corresponding scatterplots. Whether a given trial was from a similar or a dissimilar block is colour coded (red and blue, respectively). Two aspects are worth noting. First, there are clear linear relations between the predictor variables dwelling, skipping, and revisiting, respectively, and the dependent variable RT. Second, the linear relationships are roughly the same for blocks with dissimilar and similar targets, as red and blue dots align without apparent discontinuity on a single linear function. As can also be seen, there are correlations among the

Table 1. Correlation matrix for the variables similarity, RT, skipping, dwelling, and revisiting in target absent and target present trials.

	Similarity	RT	Skipping	Revisiting	Dwelling
Similarity		.37	-.27	.22	.23
RT	.64		-.87	.56	.33
Skipping	-.57	-.71		-.45	-.11
Revisiting	.37	.68	-.37		.06
Dwelling	.35	.65	-.33	.12	

Note: Entries below diagonal are correlations for target absent trials and entries above diagonal are correlations for target present trials. Correlations were calculated on trial measure. Bold coefficients are statistically significant ($p<.05$).

predictors (revisiting, skipping, and dwelling), complicating a direct interpretation of these bivariate correlations.

To take into account the correlations among the predictors and to obtain the unique effects of the predictors on RT, we analysed the data by regressing RT on dwelling, skipping, revisiting, and similarity. We used a linear multilevel regression with random intercepts for the 12 subjects to disentangle within-subject variations from between-subject variations in dwelling, skipping, revisiting, and search time. Metrical variables were z-transformed prior to analyses in order to make regression coefficients comparable. For the experimental factor target-distractor similarity, low similarity was dummy-coded as zero and high similarity was coded as one. Multilevel models do not have clear-cut degrees of freedom for t -values. With a high number of observations, however, t -distributions converge with the standard normal distribution. Therefore, we interpreted empirical t -values exceeding a value of ± 1.96 as significant.

Target absent trials

Table 2(a) shows the results for predicting trial RTs on the basis of 464 target absent trials. There were no indications of strong collinearity among the predictor variables as indicated by the *variance inflation factor* (VIF), with all $1/VIF > .61$. All predictors revealed significant effects, with revisiting and dwelling having a somewhat larger unique effect on trial RTs than skipping and similarity. Marginal R^2 was .92 (Nakagawa & Schielzeth, 2013).

Target present trials

Target fixations are omitted from the analysis of target present trials to be consistent with the previous analysis. That is, only distractor fixations are analysed. We applied the same trial based multilevel regression model as for the target absent trials to target present trials. The total number of observations was 431. Indications of collinearity were low, $1/VIF > .76$. All slopes were significant (see Table 2(b)). That the effect of skipping is dominating in this analysis is no surprise as, in target present trials, the target is found after variable numbers of inspected distractors. Thus, skipping is expected to be the most important determinant of RT. Marginal R^2 was .84.

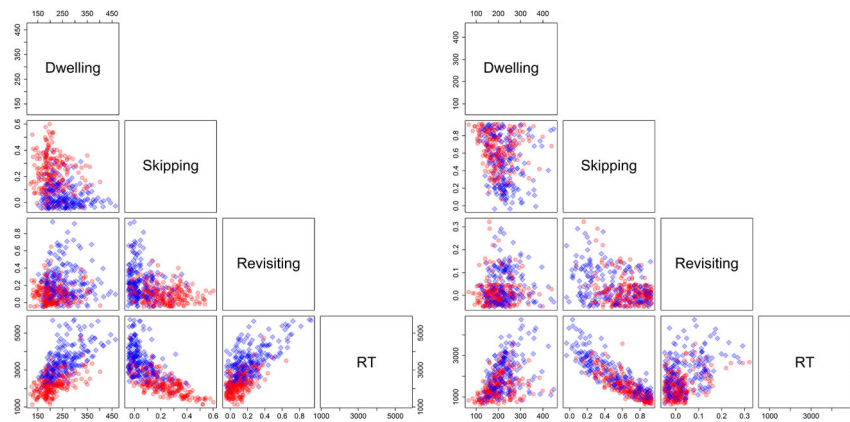


Figure 4. Bivariate relationship between trial search times (RT), revisiting rates (Revisiting), skipping rates (Skipping), and dwell times (Dwelling), for distractors in target absent trials (left panel) and target present trials (right panel) per participant. Target-dissimilar and target-similar distractors are presented as red circles and blue diamonds, respectively.

Table 2. Linear multilevel regression of target absent and present trial reaction times on dwelling, skipping, revisiting, and similarity as fixed effects and random intercepts for participants.

Target absent trials	<i>B</i>	<i>SE(b)</i>	<i>t</i>
Intercept	−.15 (.08)	.03	−4.72
Dwelling	.43	.02	25.11
Skipping	−.31	.02	−17.33
Revisiting	.44	.02	27.63
Similarity	.31	.04	8.51
<i>Target present trials</i>			
Intercept	−.11 (.21)	.06	−1.72
Dwelling	.16	.02	8.53
Skipping	−.74	.02	−37.48
Revisiting	.18	.02	9.56
Similarity	.20	.04	5.69

Notes: *b* = regression coefficient; *SE* = standard error of regression coefficient; models allowed for random intercepts between subjects; estimation method was full maximum likelihood; with the exception of similarity, all metrical variables were z-transformed prior to analyses; for similarity “dissimilar target” was coded as zero and “similar target” as one; standard deviations of random intercepts are reported in brackets; bold coefficients are statistically significant by *t*-values exceeding ± 1.96 . For target absent trials the regression was based on 464 observations. Here, both marginal R^2 (only fixed effects) and conditional R^2 (both fixed and random effects) were .92. For target present trials the regression was based on 431 observations. Marginal R^2 was .84 and conditional R^2 was .88 in target present trials.

Explaining the similarity effect

The following analyses targeted the contribution of skipping, rescanning, and dwelling to the similarity effect in our visual search task and were based on the condition averages per participant. We define the similarity effect on search performance as the difference in RT between similar and dissimilar blocks. Thus, to account for the similarity effects, the differences in RT (similar-dissimilar) were regressed on the differences (similar-dissimilar) in skipping, rescanning, and dwelling, respectively, via ordinary least squares regression. Table 3 presents the correlations for target absent and

target present trials. Figure 4 shows the scatterplots. Each point corresponds to one participant and represents the difference in the respective variable between the similar and the dissimilar target condition.

Target absent trials

For target absent trials, there were no indications of strong collinearity among the predictor variables, with all $1/VIF > .91$. The multiple regression yielded significant effects for dwell time, $t(8) = 8.21, p < .001$, and revisiting, $t(8) = 3.85, p = .005$ (skipping: $t(8) = -1.43, p = .191$). The standardized weights are $b = .83$ for dwell time, $b = -.15$ for skipping, and $b = .40$ for revisiting (all *SEs* between .10 and .11). For the whole model, explained variance was $R^2 = .92$. To summarize, dwelling and skipping contributed significantly to the similarity effect in target absent trials, while skipping did not.

Target present trials

For target present trials, all $1/VIFs$ were $> .91$. The regression analysis for target present trials rendered

Table 3. Correlation matrix for the differences (similar-dissimilar) in RT, skipping, dwelling, revisiting, and guidance in target absent and target present trials based on subject's averages.

	RT	Skipping	Revisiting	Dwelling	Guidance
RT					
Skipping	−.01				
Revisiting	.47	.26			
Dwelling	.88	.04	.12		

Note: Entries below diagonal are correlations for target absent trials and entries above diagonal are correlations for target present trials. Bold coefficients are statistically significant, $p < .05$.

effects of dwelling, skipping, and revisiting, $|ts(8)| > 2.31$, $ps < .050$. The standardized weights for the effects were $b = .62$ for dwelling, $b = -.32$ for skipping, $b = .56$ for revisiting (all SEs were between .13 and .14, $R^2 = .86$).

Target guidance

We found some target guidance, even though it was not particularly strong. How is this guidance advantage mediated? What distinguishes a person with high ability to use guidance from another with low ability to use guidance? Table 4 presents the correlations. The difference in fixation latency for the target and the foil served as index for guidance. As can be seen, good guidance use is mainly correlated with good skipping in present trials, which is what it should be. The other correlations were not significant.

We went a step further and asked whether average search times in target present trials can be predicted by means of linear regression, with average guidance, dwelling, skipping, revisiting, and similarity as predictors (see Table 4 for correlations). Each participant contributed two sets, one for similar and one for dissimilar targets, of four averages, which were average dwell time, average revisiting rate, average skipping rate, and average guidance strength. All $1/VIFs$ were $> .17$. The effect of guidance was significant, $t(18) = 2.64$, $p = .017$. As before on the trial level, dwelling, skipping, and revisiting were significant as well, $|ts(18)| > 4.19$, $ps < .001$. The effect of similarity was not significant, $t(18) = -0.95$, $p = .355$. Standardized weights were: $b = .16$ for guidance, $b = .45$ for dwelling, $b = -.53$ for skipping, $b = .30$ for revisiting, and $b = -.15$ for similarity (SEs were .06, .06, .12, .07, and .16, respectively). Curiously, the unique effect of guidance has a positive sign. In other words, more guidance (as reflected by shorter fixation latencies to targets than to foils) is associated with longer search times, when the

influence of the other predictors is held constant (we will return to this in the Discussion).

We also analysed whether the similarity effect can be explained by the difference between the strength of guidance with similar and dissimilar targets. Note that this is the same regression as presented before for the similarity effect in target trials, with the additional inclusion of differential guidance. All $1/VIFs$ were $> .63$. A model comparison, however, yielded no significantly improved model fit ($\Delta R^2 = .01$, $F(1, 7) = 0.83$, $p = .393$); that is, in this model the unique effect of guidance did not significantly contribute to the similarity effect.

Discussion

General results and analyses of variance

Search times were longer in the difficult search condition with the similar target than in the easy search condition with the dissimilar target. The similarity effect is consistent with previous research and the central predictions of Duncan and Humphreys (1989). The similarity effect is substantial in both target and absent trials, and it is indeed also stronger in absent trials.

The eyes fixated on the target in almost all trials, indicating that foveal processing of the target is preferred or may even be necessary in the present task. Most, but not all, of the distractors in absent trials were fixated, whereas distractor fixations were much reduced in target trials. This pattern is largely consistent with a serial search that stops once the target is found, which seems to be the "default" in difficult search and is probably not due to specifics of the present task and stimuli. That not all distractors are fixated in absent trials might be due to strategical factors, as implied by the variable threshold account (Chun & Wolfe, 1996), or it could be due to errors from memory failure, as implied in the FVF model (e.g., Hulleman & Olivers, 2017).

Distractor skipping was higher in easy search with dissimilar targets than in difficult search with similar targets. This result was true for both present and absent trials, and is thus consistent with Chun and Wolfe's (1996) threshold account. Also in accord with this account, the target afforded guidance, as indicated by the significant selection latency difference between the target and the foil target. However,

Table 4. Correlation matrix for the variables similarity, RT, skipping, dwelling, revisiting, and guidance in target present trials based on subject's averages.

	Similarity	RT	Skipping	Revisiting	Dwelling
RT	.70				
Skipping	-.79	-.86			
Revisiting	.63	.80	-.74		
Dwelling	.45	.80	-.55	.42	
Guidance	-.29	-.31	.55	-.27	-.26

Note: Bold coefficients are statistically significant, $p < .05$.

somewhat surprisingly, the conditions with similar and dissimilar distractors did not significantly differ in the amount of guidance. This result is remarkable, given the sizable effect of similarity on RT. It is a first indication that visual guidance by the target is not the only variable that causes differences in search efficiency. Skipping is also predicted to differ by the FVF model (Hulleman & Olivers, 2017), as this model assumes that efficiency is gained by processing more items within a single fixation.

Dwell times on distractors were systematically influenced by target-distractor similarity. Thus, dwelling would explain a large portion of the similarity effect in target absent trial search times, where almost all items are fixated. The present results are consistent with the claim that dwell times vary with search difficulty (Becker, 2011; Gould, 1967; Hooze & Erkelens, 1998; Horstmann et al., 2016), and that dwell time differences contribute substantially to search efficiency differences, including in target present trials. The robust effects of similarity on dwell times question the assumption of prominent search theories that treat attentional dwell time (GS; Wolfe, 1994) or fixation dwell times (TAM; Zelinsky, 2008; FVF; Hulleman & Olivers, 2017) as a constant parameter in their models.

Similarity had substantial effects on distractor revisiting, which had been proposed as a cause of search performance in models such as FVF (Hulleman & Olivers, 2017; see also Humphreys & Müller, 1993). Distractor revisiting was higher in absent than in present trials. In easy search, on average about one distractor was revisited per absent trial; in difficult search, this happened more than twice as often. The higher number of revisited distractors in absent than in target trials can be at least partly explained by the fact that search is terminated earlier in a target trial than in an absent trial (self-terminating search). Thus, if revisiting occurs on a constant portion of gaze shifts, it follows that the sum of revisits at the end of the trial should be higher in absent than in present trials.

The highest number of revisits was registered for targets. This suggests that the eyes often left the target before it was successfully recognized, while nonetheless sufficient evidence for target presence had been accumulated. This in turn implies that decision processes do not stop when the next shift of gaze is executed, but rather continue in parallel to

the next eye movement. It also suggests that initiating the next shift is partly independent from target identification (see Godwin, Reichle, & Menneer, 2017). Given the substantial amount of revisiting, this variable seems to be underrepresented in theoretical accounts of search efficiency.

To summarize the general results from the ANOVAs, similarity had effects on reaction times, guidance, dwelling, skipping, and revisiting. It fell just short of significantly influencing our measure of guidance.

The regression analyses

The ANOVAs reveal that similarity has an effect on RT, dwelling, skipping, and revisiting, meaning that dwell time, skipping rate, and revisiting rate are different for easy and difficult search.

The regression analysis focusses on a related question: What is the contribution of dwelling, skipping, and revisiting to search times? In our analysis, we focused on the level of individual trials: how much are variations in search time from trial to trial determined by the dwelling, skipping, and revisiting of distractors in that trial?

We found somewhat different patterns of results for absent and present trials. Absent trials reflect most purely distractor processing. Dwelling, skipping, and revisiting were all correlated with search time, as would be expected on the basis of the ANOVAs, and there were also substantial correlations between the variables. Linear multilevel regression models were used to assess the unique effects of the predictors in the dependent variable. The effects of dwelling and revisiting were strongest, indicating that dwelling and revisiting explain most of the variance in search times. The effect of skipping was smaller but still substantial. It is noteworthy that the effect of skipping in absent trials was not as strong as one might expect based on the threshold hypothesis (i.e., Chun & Wolfe, 1996), where skipping is the only systematic source of variance acting on target absent RTs. An interesting detail is that similarity had an effect on search times that was not mediated by the other predictors. Therefore, the simple linear model with dwelling, skipping, and revisiting as predictors does not fully cover similarity-based effects. Possibly, similarity had an effect on other variables that were not analysed here,

such as the time the participants waited before they started searching.

The results pattern was different for present trials. The impact of dwelling and revisiting was statistically significant but numerically reduced. In contrast, the impact of skipping strongly increased. We interpret this result as follows. The strong effect of skipping in present trials is an almost trivial consequence of serial search without much guidance. Without much guidance, the target is effectively found by chance, that is, it is found as the first, second, third, etc., item with the equal probability of $p = .10$. If the target is found after a variable number of visited items, and if search is terminated upon finding the target, it follows that search times must be highly correlated with the number of visited items (and, by implication, with the number of skipped items). That the effects of dwelling and rescanning are lower results mainly from the fewer number of fixated items in present trials compared to absent trials.

To summarize, support for determinants of search times other than guidance were very prominent in absent trials, and somewhat weaker in present trials. Target present trial search times are dominated by the variable number of fixated items, as would be expected for a difficult search that does not afford much guidance.

Explaining the similarity effect

We also made progress in unravelling the mechanisms determining the similarity effect in visual search, that is, the shorter search times for a target which is relatively dissimilar to the distractors. In absent trials, dwelling was the best and the only significant predictor of the similarity effect, whereas skipping and revisiting were not significant. Revisiting was also significant but clearly had less of an impact. The effect of skipping was not significant. In present trials, dwelling, skipping, and revisiting all contributed to the similarity effect (in this order). Comparing present and absent trials, the influence of dwelling decreased, while the influence of skipping increased. It is noteworthy again that dwelling figured so prominently here because guidance centred models such as GS and TAM do not consider variations in dwelling at all. Moreover, it is not uncommon to explain search efficiency differences by reference to guidance. The present results

indicate that search efficiency differences may arise quite independently from guidance.

Why did similarity influence dwelling, skipping, and revisiting? Dwelling is influenced by a number of variables (Becker, 2011; Gould, 1967; Hooe & Erkelens, 1998), in particular visual difficulty, target-distractor similarity, and the number of targets (i.e., the heterogeneity of the instances within the target category). Dwelling is essentially the time spent processing an item (or a group of items), such that variables that influence processing time are expected to influence dwell time and, in turn, search times.

Rescanning is plausibly influenced by similarity when the actual dwell time on an item was too short to yield a proper decision. There is evidence that dwell times are partly determined in advance, based on expected search difficulty (cf. Hooe & Erkelens, 1998), and that information processing of stimulus and deciding on or error monitoring regarding stimulus $n-1$ progress in parallel (e.g., Pashler, 1994; Remington, Lewis, & Wu, 2006). That is, searching is not a completely controlled process, but often has a ballistic component, where the selection of the next stimulus is issued after some time, or after some threshold in processing has been reached. Thus, if the processing requirement for an individual item is longer than the average processing time, and if the system detects the error, rescanning would be required. Moreover, rescanning may have a strategic component. For instance, with a dwelling-rescanning trade-off, one might choose for a fast pace in scanning (with short dwell times), at the cost of an increased need to rescan items (Godwin et al., 2017).

Skipping in target absent trials may depend on similarity because participants have some idea when they would have found a target, if present, and terminate search when the current search time exceeds this estimate, or because the threshold for continuing search is set higher in easy search (cf., Chun & Wolfe, 1996). This is consistent with the results pattern. However, note that there are other possibilities. For example, it is possible that skipping rates are different for easy and difficult searches because in easy search it might be sometimes possible to process more items during one fixation (Venini, Remington, Horstmann, & Becker, 2014). This would be expected in the context of the FVF Model (Hulleman & Olivers, 2017). Even though the present search is very hard and often only one item would be processed during a

single eye fixation, the field of view would be expected to be larger in the easy condition, and thus occasionally a neighbouring item might be processed together with the fixated item. Accordingly, skipping can be explained without assuming an adaptive threshold.

Guidance

The measure of guidance we used was the difference in selection latency between the foil in absent trials and the target in present trials. With this procedure, target selection latency is corrected for the effects that are caused by distractor processing independent from target presence (as given by the selection latency of the foil target in the absent trials). This yields a continuous measure of the search advantage for the target in a target present trial over the foil in an absent trial. High values indicate strong guidance. Two guidance measures are calculated for each participant: one for a similar target and one for a dissimilar target.

The results concerning guidance by the target were mixed. Fixation latency was much shorter for the dissimilar than for the similar target. However, we argue that this is no unequivocal indicator for guidance, because similarity has other effects that are independent from guidance, in particular on dwelling and revisiting. These independent effects would thus also affect fixation latency. In order to subtract these influences from our measure, we used the fixation latency of a corresponding non-target stimulus (i.e., the foil target) as a reference. Thus, our guidance measure was the difference between the latency of the fixation on the foil target and the target. Contrary to expectations, our guidance measure was not significantly influenced by similarity in the ANOVA analysis (i.e., the interaction between similarity and target type was not significant). Likewise, the guidance measure did not contribute independent variance explaining the similarity effect when entered in the regression.

It might be objected that this procedure is biased against finding evidence for guidance. For example, on Chun and Wolfe's (1996) threshold account, more target guidance would register in more skipping in present trials, and indirectly via the change in threshold for continuing search in absent trials. Thus, taking the difference between the target selection in

target trials and foil selection in absent trials effectively subtracts out (a portion of) the guidance effect. According to this argument, the distractor skipping rate in present trials would be the ideal measure of guidance.

A problem with this approach is that skipping may well have other causes than just guidance. According to attentional engagement theory (AET; Duncan & Humphreys, 1989), more skipping results from distractor grouping and the ability to reject similar distractors simultaneously. In the FVF model, skipping would be the result of using a larger FVF for single fixations. It might be noted that these conceptions are more parsimonious than the threshold account, because AET and FVF assumed the same common cause for present and absent trials, while the threshold account needs two principles, one for target trials (guidance) and one for absent trials (the adaptive threshold).

Our regression analysis of the search times that included guidance found the effects of dwelling, skipping, and revisiting to be strong. This is an interesting result because it indicates that dwelling, skipping, and revisiting have effects on search time that are independent from guidance. Guidance itself had a positive weight, indicating that guidance predicts longer search times. We interpret this result as follows. Guidance should influence search times in particular by changing the number of inspected distractors, that is, it should change skipping rate. This prediction is supported by the bivariate correlation between guidance and skipping. When guidance and skipping are entered into the same linear model, their common variance is partitioned out. On this account, the analysis would indicate that there is little influence of guidance that is not mediated by skipping. Concerning the paradoxical regression, individuals good at using guidance may benefit by more successfully skipping distractors, but there may be a small associated cost. For example, using guidance signals might entail tuning to an additional information channel. Individuals who use guidance more would be slowed more by processing the additional information relative to individuals using guidance less.

Implications for models of visual search

While the skipping results are largely in accord with Chun and Wolfe's version of GS, the strong effect

that similarity has on dwell time and the strong effect that dwell time has on overall search performance indicate the need for an extension. The same argument applies to revisiting. One might argue that the data were all irrelevant to GS because GS is a model of visual search and not a model of eye movements. However, even then, it seems difficult to reconcile the substantial role of dwelling with a model that assumes a fixed dwell time.

A similar objection applies to TAM. In contrast to GS, TAM is a model of eye movements in visual search. Thus, the present results have immediate implications for TAM, as this model explains search speed and the effects of target-distractor similarity exclusively via guidance. The evident role that dwelling plays in determining search speed is not captured by the model thus far.

Finally, the FVF model, which is also an explicit model of eye movements, is supported by the results for skipping and revisiting but similarly falls short of accounting for the dwell time results. The model assumes random sampling of groups of stimuli, with a limited memory for already tested positions, which predicts substantial rates of skipping and revisiting. Obviously, this model also has difficulties with our dwell time results, because dwelling is assumed to be fixed in the FVF model.

Admittedly, even though we point to some weaknesses of prominent models of visual search, we do not offer a new model of visual search here. We believe that prominent models of visual search such as GS or TAM already provide promising descriptions of many aspects of the search process, as does the more recent FVF model. We rather advocate the view that previous models neglect the importance of dwelling as a determinant of search behaviour. The present results corroborate this claim. They show that dwelling has a substantial effect on search speed, and that dwelling was the most important predictor of RT and RT differences in several of the regression analyses.

Comparison with Horstmann et al. (2016)

Horstmann et al. (2016) used a similar task with a similar aim. As we observed in the introduction, this previous study is vulnerable to critique because it used low set sizes and a highly structured display. Low set sizes and a structured display would not

(according to our assessment) influence dwell times, but may have led to generally low skipping rates (because preplanning a complete scan is easy with a structured display) and low rescanning rates (because the low set size approaching VSTM capacity of four items would allow maintaining already visited positions in VSTM). In agreement with this reasoning, we found rescanning and revisiting to be more important in the present study, which used a higher set size and a less structured display. Apart from that, however, the importance of dwelling was replicated, corroborating our view that variations of dwell time should be included in models of visual attention and visual search.

We also conducted the regression analysis on the level of trials rather than on the level of condition means. We think that it is noteworthy how well the general pattern of results was replicated on the trial level. Condition means may not always reflect what is happening on an individual trial. They may rather reflect the general – or average – strategy that is used. In contrast, the present regression analyses on the trial level reflect more accurately the mechanics of visual search.

The effects of skipping and revisiting were strong in the present analysis. This result is consistent with the assumption (made in the introduction) that revisiting (and possibly also skipping) are more frequent when the previously visited item positions cannot be tracked completely. A reasonable assumption is that the number of positions that can be remembered during search is about four, which is the same as VSTM capacity (e.g., Hulleman & Olivers, 2017). This would explain why the present study, with a set size of 10, found more revisiting and skipping than the previous study, with a set size of four.

Notes

1. Note that in this and in the following analyses, the category of distractors always excluded the foil target.
2. We additionally analysed lag-2 revisits as a variant of revisits that occur when a stimulus is revisited after a single off-stimulus fixation. Lag-2 revisits presumably reflect ongoing stimulus processing even after the next saccade has already started (Godwin et al., 2017). In our experiment, the probability of lag-2 revisits increased with target-distractor similarity both on targets (.11 vs. .24) and on distractors (.01 vs. .03), $t_s > 3.17$, $p_s < .009$. The higher number of lag-2 revisits to the target than

to the distractor indicate that target identity information indeed controls lag-2 revisits.

3. One might argue that the skipping of distractors before the target is selected is a simple measure of guidance. An analogous analysis that asks how many items are visited before the target versus the foil target, however, reveals the same results pattern with main effects and without a clearly significant interaction between similarity and stimulus type (i.e., target vs. foil target). Guidance saved the participant from fixating .87 distractors for the dissimilar target and .25 distractors for the similar target, a difference that, however, just failed to be significant, $p = .06$.

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